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INVESTIGATION OF DISPLACEMENT LIMITATIONS FOR LASER SPECKLE PHO--ETC(U)
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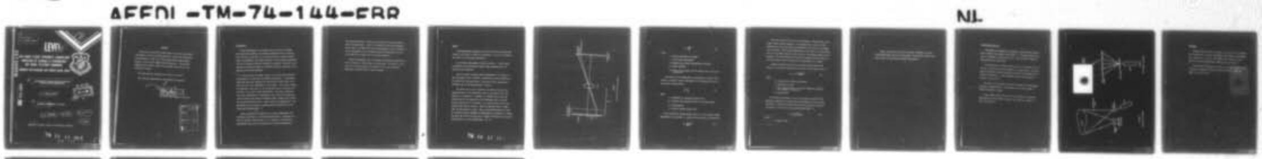

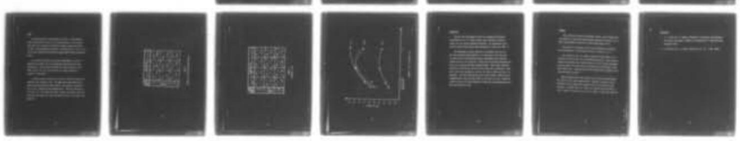

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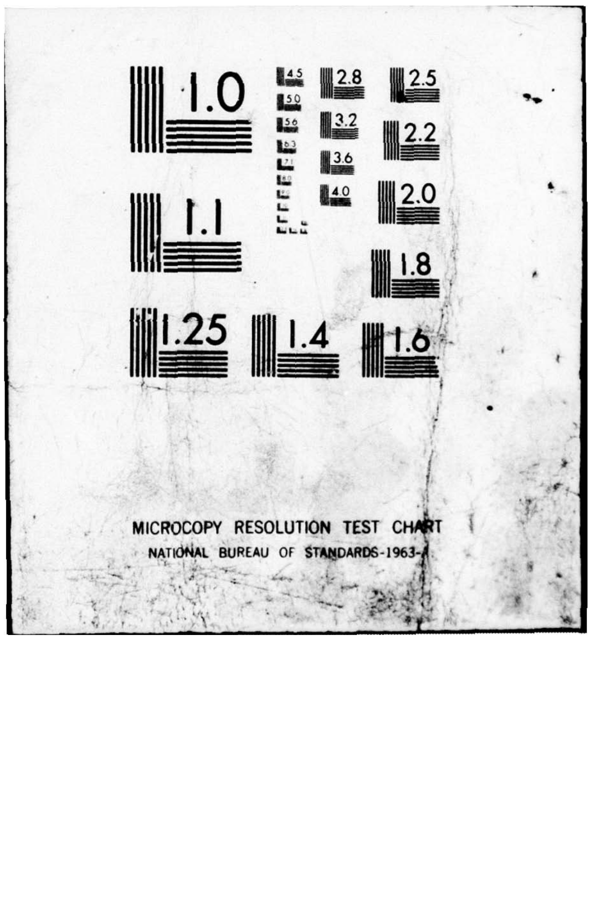
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DIRECTOR OF SCIENCE & TECHNOLOGY
AIR FORCE SYSTEMS COMMAND
WRIGHT-PATTERSON AIR FORCE BASE OHIO

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(6) INVESTIGATION OF DISPLACEMENT LIMITATIONS
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(10) MARK R. LENCI

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FOREWORD

This work was conducted by Cadet Mark R. Lenci under Task 146702 "Thermoelastic Structural Analysis Methods", Project 1467 "Structural Analysis Methods", while on the USAF Academy Cadet Summer Research Program at the Air Force Flight Dynamics Laboratory. The work was suggested by Dr. Frank D. Adams of the Analysis Group and he acted as Technical Advisor.

The manuscript was released by the author in July 1974.

This Technical Memorandum has been reviewed and approved.

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Introduction

Speckle photography is a relatively new laser optics technique which shows much promise in the field of experimental stress analysis. The objective of this report is to provide the user of speckle photography with guidelines concerning the amount of test specimen displacement that can be tolerated when this technique is employed. Experiments were performed to determine limits as a function of optical parameters such as magnification and lens aperature.

A double exposure procedure, similar to that used with holographic interferometry, is used with laser speckle photography. A photographic image made using this technique has each speckle recorded twice; once before and once after displacement of the subject. The distance between corresponding speckle pairs on the photographic plate is directly proportional to the local in-plane displacement. Data may be extracted from these specklegrams by illuminating a local area of the image with a small diameter laser beam and observing Young's fringes which modulate the resulting diffraction halo. These fringes are perpendicular to the displacement vector and have a spacing inversely proportional to the displacement magnitude (Ref. 1).

Speckle photography is sensitive to in-plane displacements and relatively insensitive to out-of-plane displacements. Holography has just the opposite characteristics, i.e., sensitive to out-of-plane displacements and relatively insensitive to in-plane displacements.

The preceding discussion indicates that holography and speckle photography are complementary. Thus, if the general nature of the displacement is known, the method best suited for measuring it may be selected. If the displacement is of an unknown nature, both methods may be used to determine the in-plane and out-of-plane components.

Speckle photography, like its complement holographic interferometry, can only tolerate a finite amount of displacement. The subject of this report is the investigation of the amount of tilt and out-of-plane displacement allowable before fringes disappear.

Theory

The displacements considered in all our work have been small with respect to the depth of field of our apparatus. First let us consider the effect of out-of-plane displacement.

Out-of-plane displacement may have two effects. It will create an apparent radial displacement and/or cause decorrelation of the speckle between exposures.

The first effect, apparent radial displacement of the object on the photographic plate, increases in magnitude in direct proportion to the radius from the optical axis. The source of this apparent displacement can be seen geometrically in Figure 1.

The reader can see that a speckle on the optical axis will not change position on the photographic plate as the subject moves from position 1 to position 2. A speckle at a definite radius from the optical axis will be displayed on the photographic plate an amount directly proportional to the radius. On a double exposure film plate, speckle pairs will be recorded. These will generate Young's fringes when the specklegram is viewed. Thus, out-of-plane movement can cause an erroneous in-plane component of displacement to be measured. Archbold and Ennos have derived an equation for speckle displacement on the photographic plate for a given displacement (Ref. 2).

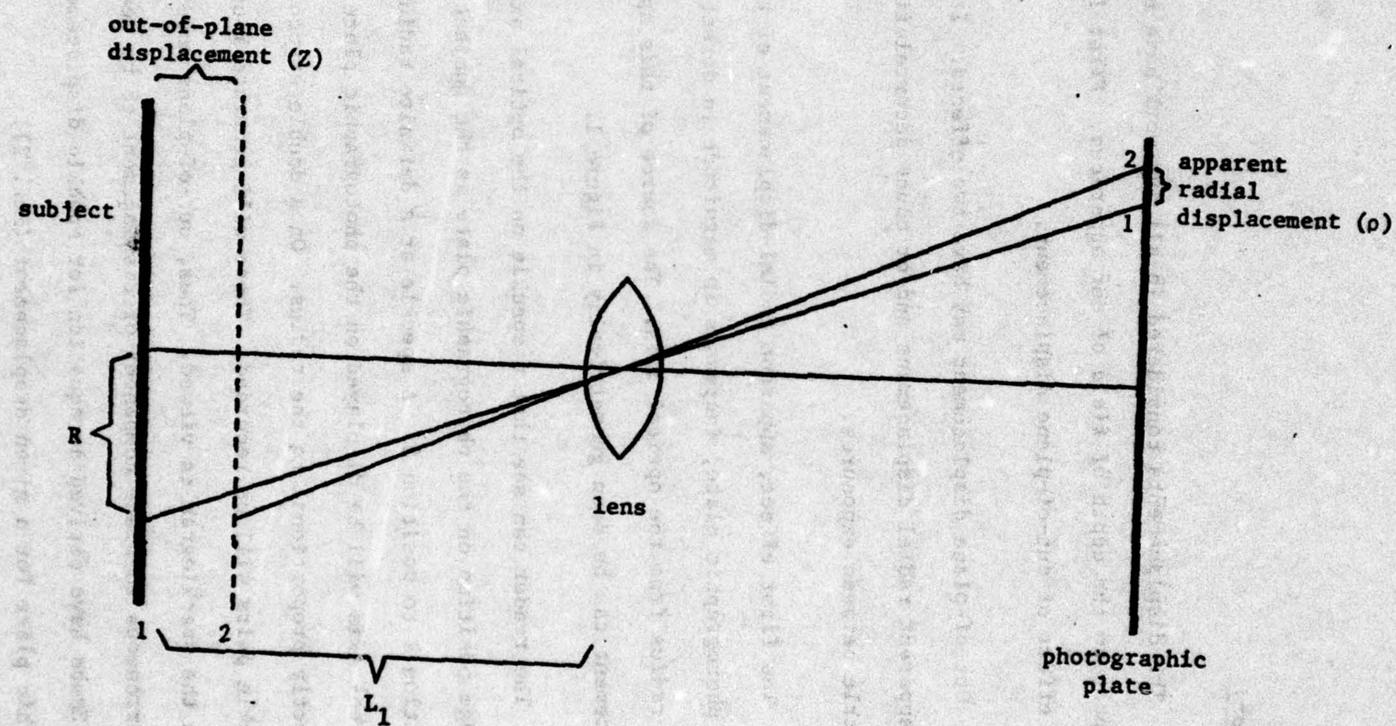

FIGURE 1

Source of radial displacement

$$\rho = \frac{ZRM}{L_1} \tag{1}$$

where:

ρ = Radial Displacement of Speckle

Z = Out-of-Plane Displacement

M = Magnification (Image Distance/Object Distance)

L_1 = Object Distance

R = Radius on the subject from the Optical Axis to the point in question.

The spacing of the fringes when the specklegram is viewed, may be related to speckle's radial displacement on the photographic plate by the Young's fringes equation:

$$\frac{\lambda}{d} = \frac{D}{L_2} \tag{2}$$

where:

λ = Wavelength of Illuminating Light Source

L_2 = Distance from Photograph Plate to the Viewing Plane

D = Fringe Spacing

d = Distance between Speckle Pairs

Since the distance between speckle pairs, d, is the apparent radial displacement of the speckle, ρ, equation one and two may be combined to:

$$D = \frac{L_1 \; L_2 \; \lambda}{ZRM} \tag{3}$$

The second effect of out-of-plane displacement is decorrelation of the speckle pattern between exposures. The speckle field, itself, is three dimensional in nature and only a two dimensional cross section is recorded on a film plate. Out-of-plane displacement of the subject, if large enough, will move the image along the optical axis and a new speckle pattern will be recorded. This new speckle pattern will not correlate with the pattern of the first exposure and no fringes will be created when it is viewed.

Archbold and Ennos have derived an equation which predicts what amount of out-of-plane displacement will result in decorrelation (Ref. 2).

$$Z = \pm 2\lambda \left[\frac{F(M+1)}{M}\right]^2 \qquad (4)$$

where:

Z = Tolerable Out-of-Plane Displacement

λ = Wavelength of Source

F = Focal Length/Diameter of Aperature (Numerical Aperature for an Object at Infinity).

M = Magnification

Out-of-plane displacement is not the only cause of speckle decorrelation. Tilting of the surface about an in-plane axis can also cause this effect. Archbold and Ennos have derived an equation to calculate the amount of tilt which will cause decorrelation (Ref. 2).

$$\theta = \frac{M}{(2.4)F\ (M+1)} \qquad (5)$$

where:

θ = Angle of Tilt

Points off the axis of tilt will also have components of out-of-plane displacement when tilt is introduced. Decorrelation in this case, may be due to tilting and out-of-plane displacement.

Experimental Apparatus

The apparatus arrangement for recording a double exposure specklegram is simply a basic camera (See Figure 2). A expanded laser beam is used to illuminate a diffuse surface and a lens focuses the image on a photographic plate (AGFA 10E75).

A flat plate with a diffuse surface served as the subject for all of the work. The subject plate was mounted on a movable table. The table could be displaced along the in-plane axis and the out-of-plane axis by using two micrometers. A third micrometer tilted the plate about a vertical, in-plane axis.

The object to lens distance is varied to produce the desired magnification or demagnification. The aperature on the lens is used to produce the desired f number.

A small diameter laser beam is used to interrogate the developed specklegram and create Young's fringes. The fringes are viewed on a screen (See Figure 3).

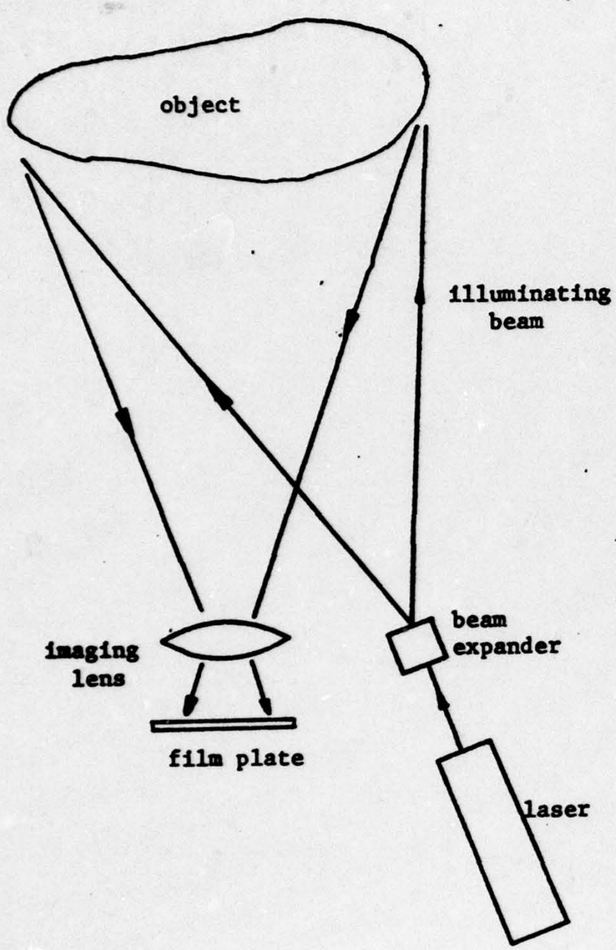

FIGURE 2

Recording Technique

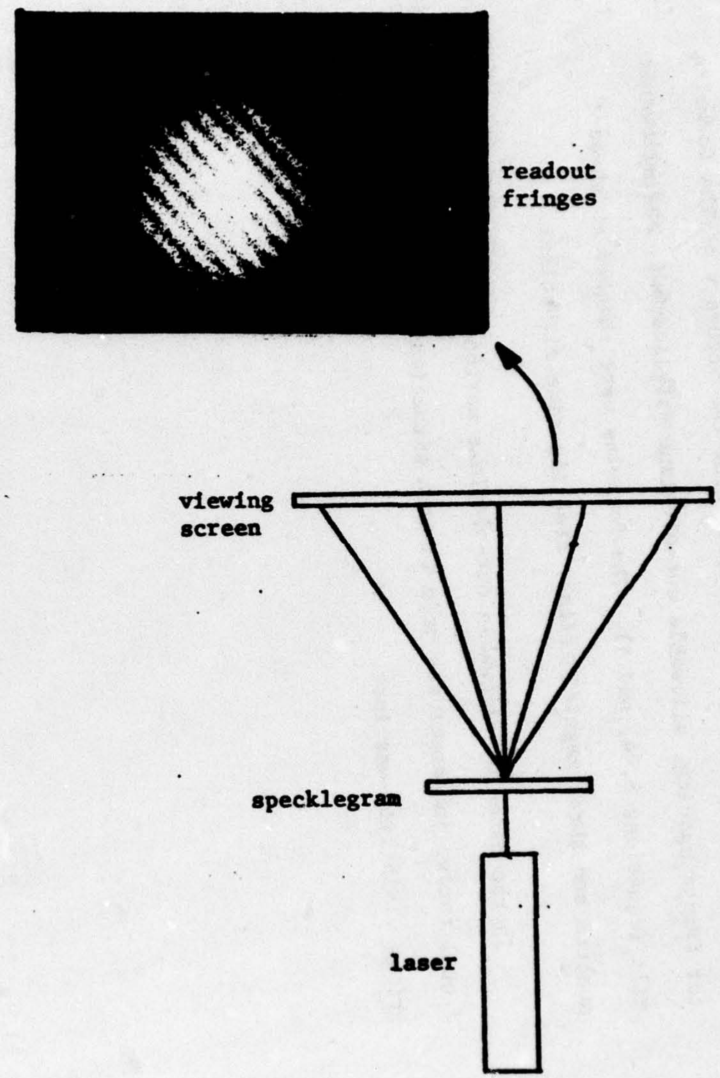

FIGURE 3

Data Readout Technique

Procedure

The data taken was used to determine the accuracy of the formulas for fringe spacing, allowable out-of-plane displacement, and allowable tilt (equations 3, 4, and 5). The formulas were checked at three f numbers and three magnifications, creating nine situations.

In the cases of allowable out-of-plane motion and allowable tilt, a qualitative judgement was made in each situation as to when the fringe visibility was lost.

Data

Speckle photography measurements were taken to check apparent radial displacement caused by out-of-plane movement of the subject. These data were collected for aperature numbers ranging from f/2.8 to f/22. The magnification parameter was varied from M = 2 to M = 1/5. In all cases measured and calculated values agreed within experimental error.

To determine allowable out-of-plane displacement, a series of exposures were made; each with increasing amounts of out-of-plane displacement. This produced experimental values which were in all cases a factor of two to three greater than those predicted by equation 4 (See Table 1).

A similar series of exposures were used to check the equation for allowable tilt (equation five). The degree with which experimental results matched calculated values varied. The largest discrepancies were at low f numbers and high magnification. Here the difference is a factor of 10. The results for high f numbers and magnification less than unity were nearly the same as calculated results (See Table 2 and Figure 4).

f number	magnification 1/5 (actual / theory)	magnification 1 (actual / theory)	magnification 2 (actual / theory)
2.8	.055" / .014"	.007" / .0016"	.0025" / .00088"
8	.25" / .12"	.035" / .013"	.020" / .0072"
22	.55" / .87"	.18" / .097"	.090" / .054"

TABLE 1

Allowable out-of-plane Displacement

actual / theory		magnification			
		1/5	1/3	1	2
f number	2.8	.25° / 1.4°	.28° / 2.1°	.44° / 4.3°	.37° / 5.6°
	8	.29° / .21°	.35° / .74°	.45° / 1.5°	.50° / 2.0°
	22	.11° / .18°	.14° / .26°	.20° / .54°	.18° / .72°

TABLE 2

Allowable Tilt

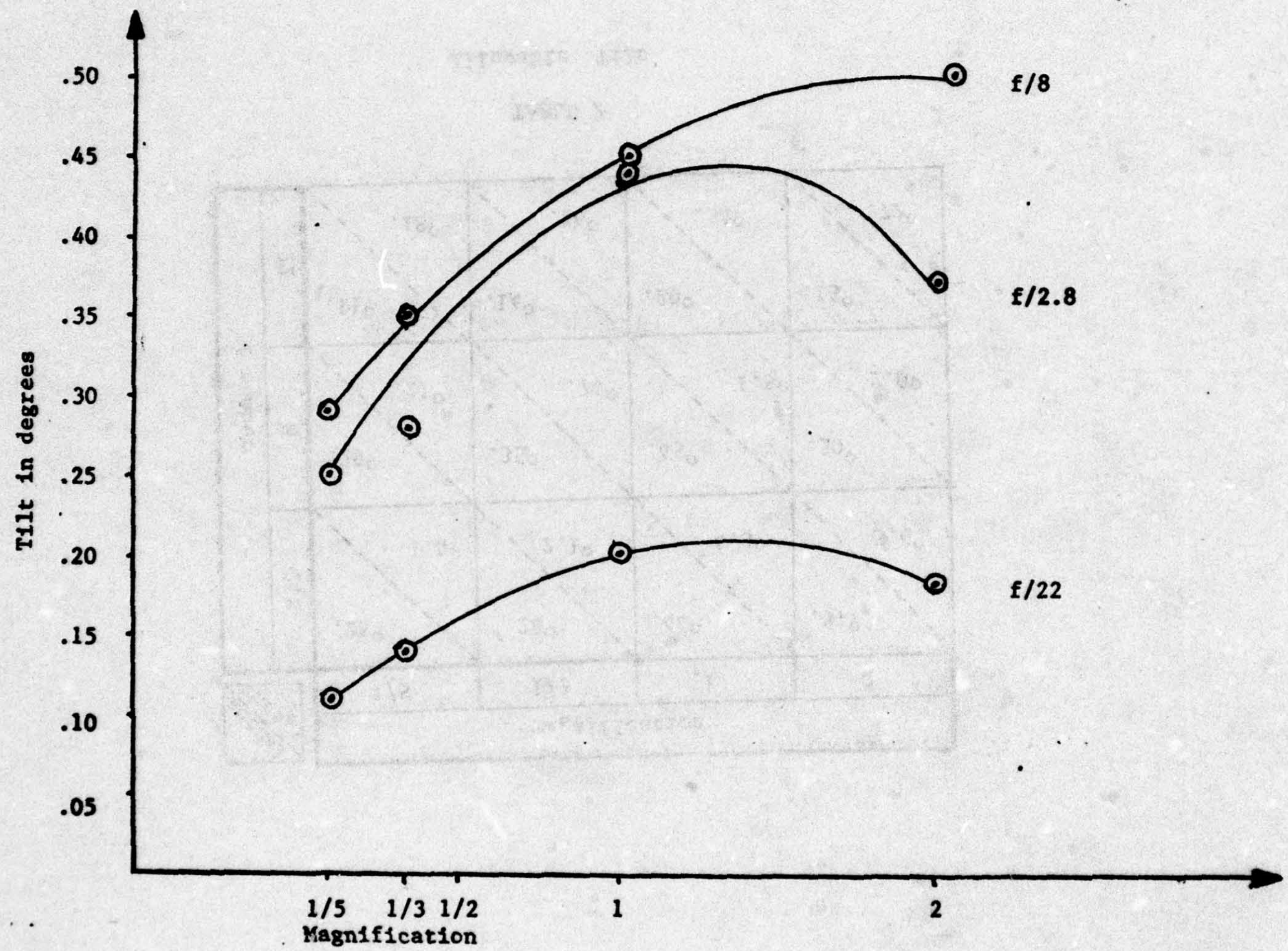

FIGURE 4 Plot of Allowable Tilt

Discussion

The fact that experimental results for allowable out-of-plane displacements are 2 to 3 times greater than predicted by equation 4 agrees with the results obtained by Archbold. He consistently found that his results were greater than predicted by a factor of 4 (Ref. 1).

The experimental results obtained for allowable tilt, plus the fact that Archbold found equation 5 to be accurate in his work, tend to indicate that the discrepancy between experimental and calculated results are due to the lens used. Notice that the greatest discrepancies are at low f numbers and higher magnifications. Under these conditions much more of the lens is used than at any other set of conditions. Using more of the lens introduces error since the lens is least accurate at its periphery. The least discrepancies were found at high f numbers and low demagnification, when the least amount of the lens is in use. Apparently Archbold did his work using demagnified images and this phenomenum may not have been observed by him.

Summary

When working with speckle photography methods, one can expect that the formula for predicting fringe spacing (equation 3) for pure out-of-plane displacements is accurate to within experimental error.

The formula for allowable out-of-plane displacement (equation 4) will underestimate the experimental value by a factor of 3 to 4.

The accuracy of the tilt formula (equation 5) will depend on the quality of the lens used in the experimental apparatus. Close agreement between experimental and calculated results for low f numbers and magnification greater than unity should be expected only when using a large, high quality lens. Discrepancies with the formula will increase as lens size and quality decrease.

Higher magnifications will tolerate more out-of-plane displacement but less tilt than lower magnifications. However, the amount of tilt tolerated at low f numbers will greatly depend on the quality of the lens used. Anything short of a large, high quality lens may result in a low f number tolerating less tilt than a higher f number (See Table 2).

References

1. F. D. Adams and G. E. Maddux, "Synthesis of Holographic Interferometry and Speckle Photography to Measure 3-D Displacements", AFFDL-TM-73-126, (September 1973).

2. E. Archbold, and A. E. Ennos, Optics Acta, 19. Nr. 4, 253, (1972).